THERMAL INSULATION

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A METHOD FOR ESTIMATING HEAT-SHIELDING PROPERTIES OF MINERAL WOOL INSULATION BASED ON SILICATE FIBROUS MATERIALS

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A method for estimation of the heat-shielding properties of gas-filled mineral wool insulators is considered, which takes into account the mechanism of interrelated heat and mass transfer processes and their intensities, depending on the service conditions, design specifics, and technological parameters of the insulating material.

Heat exchange in fibrous heat-insulating materials which constitute highly disperse gas-filled systems, is a complex process which includes heat transfer by conduction, radiation, and convection and is implemented by means of :

– conductive heat transfer in the fiber which forms the matrix of the porous structure of a heat-insulating material;

– radiative heat exchange inside the absorbing, reflecting, and dissipating medium of the inter-fiber space;

– convective flows of the gas filling the inter-fiber space, caused by the temperate difference between the boundary surfaces of the heat-insulating structure.

The heat-shielding properties of fibrous materials are usually determined by employing relationships based on the Fourier law, which, strictly speaking, are only true for homogeneous solid bodies in which heat transfer in the presence of a temperature gradient proceeds only in the form of heat conduction.

It is obvious that heat transfer in such an approach is a generalized characteristic of the thermal conductivity of the material, i.e., the effective thermal conductivity λ_{ef}:

$$\lambda_{ef} = \lambda_q + \lambda_r + \lambda_c, \tag{1}$$

where λ_q, λ_r, and λ_c are conductive, radiative, and convective heat transfer, respectively.

The present study, on the basis of the effective heat transfer concept, considers a method for the estimation of heat-shielding properties of gas-filled fiber insulation, which is based on contemporary concepts and takes into account the mechanism of interrelated heat- and mass-exchange processes and their intensities, depending on the operating conditions, structural specifics, and technological parameters of the insulating material.

Conductive heat transfer. An analysis of data obtained on the basis of the variation principle of the continuous medium mechanics and other theoretical models for conductive heat transfer, as well as semi-empirical models including experimentally determined coefficients, demonstrated that in using these coefficients, one can obtain values which are the closest to the experimentally found values of thermal conductivity [1 – 5].

Let us consider such a model described in [5], which gives satisfactory results in the calculation of conductive heat transfer in heat-insulating materials extensively used for heat-insulating structures in industrial insulation.

The calculation formulae of this model used for determination of the conductive heat transfer for insulation in the dry state have the following form:

$$\lambda_q = \frac{1}{(1-a)/\lambda_1 + a/\lambda_2}; \tag{2}$$

$$\lambda_1 = \frac{1}{(1-m)\lambda_f + m\lambda_g}; \tag{3}$$

$$\lambda_2 = \frac{1}{(1-m)\lambda_f + m/\lambda_g}, \tag{4}$$

where a is the structural coefficient (found experimentally); m is the porosity of the insulating material, fraction of unity;

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λ_f is the heat conductivity of the fiber; λ_g is the heat conductivity of the gas filling the porous structure of the material.

The proposed model also makes it possible to determine the conductive heat transfer of a moist material:

$$\lambda_q^m = \frac{1}{(1-a)\lambda_1^m + a/\lambda_2^m};$$

$$\lambda_1^m = \frac{1}{(1-m)\lambda_f + W\lambda_f + (m-W)\lambda_2};$$

$$\lambda_2^m = \frac{1}{(1-m)/\lambda_{av} + W/\lambda_w + (m-W)/\lambda_g},$$

where λ_w is the heat conductivity of water; W is the relative volume moisture of the insulation related to the relative moisture content of the material U (kg of moisture per kg of dry mass) by the relationship $W = U\gamma/\rho_w$ (ρ_w is the water density; γ is the volume weight).

Based on formulae (2) – (4), it is possible to calculate the conductive heat transfer at any temperature, taking the values λ_f and λ_g at the average temperature of the insulation t_{av}.

The conductive heat conductivity of a moist material can be determined subject to the condition:

$$5°\text{C} \le t_{av} \le 25°\text{C}.$$

Heat transfer by radiation. An analysis of domestic and foreign publications [6 – 12] demonstrated that the relationships describing the radiant heat conduction process in fibrous materials all have the same structure:

$$\lambda_r = f(d_f, m, a, b, c)\, kT_m^3,$$

where d_f is the fiber diameter; a, b, and c are the radiation properties of the fibrous medium; k is the Boltzman constant; T_m is the mean temperature of the insulator.

For comparative analysis of the methods for determining the radiation heat transfer in fibrous materials proposed by various researchers, radiative thermal conductivity was calculated for fiberglass insulator with the volume weight 50 kg/m^3 and the fiber diameter 6×10^{-6} m in accordance with the calculation relationships recommended in [7 – 12] (Fig. 1). A significant spread in the data is observed, nearly by the order of magnitude. The best convergence is seen in the results of methods [10 – 12].

This fact appears to indicate that the best approximation to the actual radiation heat transfer in fibrous insulating materials is provided by the model suggested in [12]:

$$\lambda = \frac{kT_m^3}{K_{at}} \frac{\pi d_f}{(1-m)}, \tag{5}$$

where K_{at} is the attenuation coefficient, which is a constant determined for various types of fibers by empirical formulae:

mullite-silica fiber

$$K_{at} = 25md_f T_m + 5 \times 10^3 (1-m)^2/T_m;$$

basalt fiber

$$K_{at} = 70md_f T_m + 5 \times 10^3 (1-m)^2/T_m;$$

mineral wool fiber

$$K_{at} = 20md_f T_m + 7 \times 10^3 (1-m)^2/T_m;$$

glass fiber

$$K_{at} = 11.2 \times 106md_f/T_m + 800(1-m)^2/T_m. \tag{6}$$

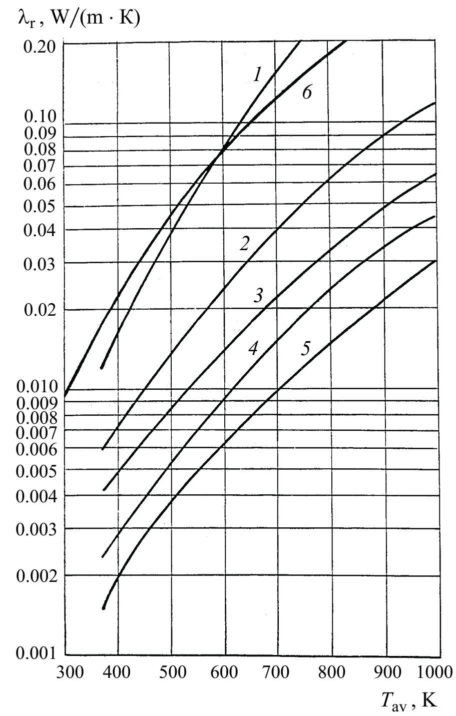

Fig. 1. Dependence on temperature of values of heat transfer by radiation in fiberglass heat-insulating materials estimated according to methods [12] (*1*), [7] (*2*), [8] (*3, 4*), [9] (*5*), and [10, 11] (*6*).

The great practical significance of this model consists in the fact that it contains calculation relationships which take into account fiber properties.

Heat transfer by convection is defined as heat transferred by convective flows of the gas filling the porous structure of the insulating material, which arise due to the difference of temperatures on the boundary planes of the heat-insulating structure.

A convenient method for studying these processes is the numerical solving of a system of nonlinear differential equations describing the joint heat and mass transfer in porous media.

The system of equations describing the stationary convection process in a flat heat-insulating layer of height h and thickness δ with impermeable lateral boundaries at which the temperatures T_1 and T_2 are maintained ($T_2 > T_1$), using the Darcy linear filtration law

$$V_{\mathrm{f}} = -\frac{\mathrm{K}}{\mu}\,\mathrm{grad}\,p \tag{7}$$

and approximation of the lift forces in the Bussinesque approximation, has the form [13]:

$$\frac{\mu U_{\mathrm{f}}}{\mathrm{K}} = -\frac{\partial p}{\partial x} + \rho g_x \beta \Delta T; \tag{8}$$

$$\frac{\mu V_{\mathrm{f}}}{\mathrm{K}} = -\frac{\partial p}{\partial y} + \rho g_y \beta \Delta T; \tag{9}$$

$$\frac{\partial U_{\mathrm{f}}}{\partial x} + \frac{\partial V_{\mathrm{f}}}{\partial y} = 0; \tag{10}$$

$$\rho c_p \left(U_{\mathrm{f}} \frac{\partial T}{\partial x} + V_{\mathrm{f}} \frac{\partial T}{\partial y} \right) = \lambda^{\otimes} \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right), \tag{11}$$

where p is the pressure; μ is the dynamic viscosity; K is the permeability coefficient; U_{f} and V_{f} are the filtration rate components; ρ is the gas density; β is the temperature expansion coefficient; c_p is the specific heat of the gas under constant pressure; T is the temperature; ΔT is the temperature difference; g_x and g_y are the projections of the free fall acceleration vector on the coordinate axes; $\lambda^{\otimes}$ is the thermal conductivity of the porous gas-filled medium without accounting for gas movement; for our case $\lambda^{\otimes} = \lambda_q$.

The results of the numerical solutions of equation system (8) – (11) are represented in the criterial form:

$$E_k = f(\mathrm{Ra}^{\otimes}, h, \delta, \varphi),$$

where $E_k = (\lambda_q + \lambda_{\mathrm{c}})/\lambda_q$; φ is the angle of the flat layer (to the horizon line); $\mathrm{Ra}^{\otimes}$ is the Raleigh filtration number:

$$\mathrm{Ra}^{\otimes} = \frac{g \beta h \mathrm{K} \rho^2 c_p \Delta T}{\mu \lambda^{\otimes}}. \tag{12}$$

Based on the numerical calculation results, it was established that in a horizontal flat heat-insulating layer ($\varphi = 0$), the effect of convection on the thermal conductivity starts to be significant at $\mathrm{Ra}^{\otimes} > 40$. An analysis of the operating temperature conditions in industrial heat-insulating structures and the filtration properties of the available fibrous materials demonstrated that the maximum value of the Raleigh filtration number for flat fibrous insulating layers is 30. Therefore, the effect of convection on horizontally arranged insulation structures can be neglected. For vertically arranged structures with $h/\delta \geq 10$ (which condition is virtually always satisfied), the following criterion equation was found based on numerical modeling data:

$$E_k = (\mathrm{Ra}^{\otimes})^{0.035}, \tag{13}$$

and for cylindrical heat-insulating structures [14]:

$$E_k = 1 + 5.9 \times 10^{-3}\,[\eta(1-\eta)]^{3/4} \exp\left((-4.29\eta)(\mathrm{Ra}^{\otimes})^2\right), \tag{14}$$

where $\eta = r_{\mathrm{p}}/r_{\mathrm{in}}$: r_{p} is the pipeline radius (r_{in} is the insulator surface radius).

In determining $\mathrm{Ra}^{\otimes}$ for a circular interlayer using expression (13), $(r_{\mathrm{in}} - r_{\mathrm{p}})$ should be substituted for h.

Having calculated the values of E_k based on equations (13) and (14), the convective heat transfer is determined from the formula:

$$\lambda_{\mathrm{c}} = \lambda_q (E_k - 1). \tag{15}$$

In order to calculate the convective component of the effective heat conductivity of fibrous insulation, one should know the permeability coefficient K for the particular material, which makes up part of the expression determining the number $\mathrm{Ra}^{\otimes}$ (12).

The expression for the permeability coefficient calculation is found used the criterion equation describing the migration of liquid or gas in a porous medium both in laminar and turbulent modes [15]:

$$f_{\mathrm{m}} = \frac{64}{\mathrm{Re}} + \frac{1}{1.14 - 21g(1 - 0.625m^{1.4})}, \tag{16}$$

where f_{m} is the resistance coefficient of the porous medium, which is part of the calculation formula:

$$\Delta p = f_{\mathrm{m}} \frac{\rho}{2g} \left(\frac{v_{\mathrm{f}}}{m} \right)^2 \frac{H S_{\mathrm{sp}}}{2m}, \tag{17}$$

where Δp is the pressure loss in filtration through a porous layer of thickness H; ρ is the moving medium density; v_{f} is the filtration rate; S_{sp} is the specific surface area of the porous medium; Re is the Reynolds number for the porous medium; $\mathrm{Re} = 4 m v_{\mathrm{f}}/(\nu S_{\mathrm{sp}})$, where ν is the kinematic viscosity.

In accordance with expression (7), to calculate the pressure loss in the laminar mode, the following formula is used:

$$\Delta p = \frac{v_{\mathrm{f}} \mu H}{\mathrm{K}}. \tag{18}$$

By equating the right parts of equations (17) and (18) and using only the right term in the right part of equation (16) for determination of f_{m}, we obtain a formula for the calculation of the permeability coefficient for a porous medium:

$$R = \frac{m^3}{4 S_{\mathrm{sp}}^2}. \tag{19}$$

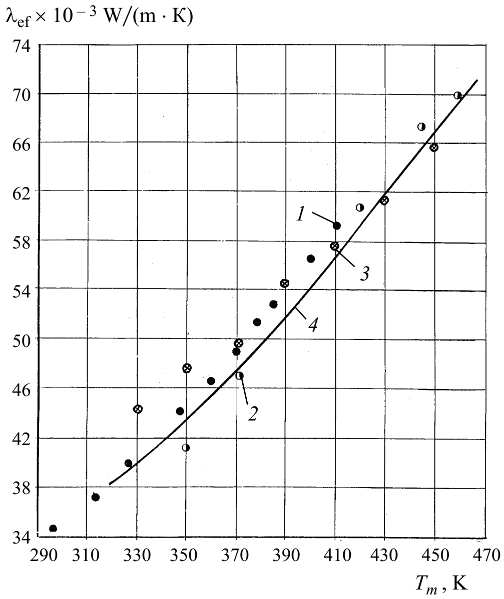

Fig. 2. Thermal conductivity of fiberglass insulating material with the mean diameter 5×10^{-6} m and the volume weight 60 kg/m^3 versus temperature: *1*, *2*, and *3*) experimental data from [10], [11], and [4], respectively; *4*) calculation results.

The specific surface area of fibrous insulation is determined by the formula:

$$S_{sp} = \frac{4(1 - m - n/\rho_f)}{d_f}. \tag{20}$$

By substituting expression (20) in formula (19), we find the expression for determination of the permeability coefficient of fibrous insulation:

$$K = \frac{m^3}{4\left(\frac{4(1 - m - n/\rho_f)}{d_f}\right)^2}, \tag{21}$$

where n is the content of nonfibrous inclusions in the fibrous insulation, kg/m^3; d_f is the fiber diameter; m is the fibrous insulation porosity determined by the relationship:

$$m = (\rho_f - \rho_m)/\rho_f, \tag{22}$$

where ρ_f is the fiber density; ρ_m is the fibrous material density.

Using formulae (1), (4) – (6), (12), (15), (21), and (22), it is possible to determine the effective thermal conductivity of the porous fibrous insulation for any temperature, which is corroborated by good convergence between the estimated and the experimental data (Fig. 2).

Thus, a model for estimating heat-shielding properties of fibrous insulation made of gas-filled silicate materials is obtained which is suitable for solving practical and engineering problems.

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